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A new model of fuel spray shape at early stage of injection in a marine Diesel engine

Abstract. The macrostructural parameters of fuel spray atomized with an injector from a marine 4-stroke Diesel engine are determined. The fuel was injected into a constant volume chamber providing an optical access. The sprays inside the chamber were visualized by means of the Mie scattering method. The marine injector was fueled by diesel oil at a constant temperature through the common rail system. The impact of ambient conditions and the geometrical parameters of the injector on the macrostructural parameters of the fuel spray was studied. The experimental results are used to propose a modified model of spray tip penetration in early stage of fuel delivered by the marine injector. The proposed model has a lower error, about 15%-34%, than the model of Hiroyasu and Arai. Moreover a new model of the evolution over time of the spray cone angle is developed.

1 Introduction

Diesel engines are commonly used sources of mechanical energy on ships. Typically, there are low-speed two-stroke diesel engines and medium-speed four-stroke ones. The source of energy in such engines is the combustion process of diesel oil or heavy fuel oil. Due to the large dimensions of marine engines and long periods of operation (many weeks of continuous operation), the air pollution may be considerable. The International Maritime Organization (IMO) has established the Marine Environment Protection Committee (MEPC), which has determined limitations on the amount of sulfur in fuel that is acceptable for the Sulphur Emission Control Area (SECA). These limitations are too low to allow the use of high fuel oil (HFO) in these SECAs. Therefore, marine diesel oil (MDO) is used. It should be noted that a marine engine with a nominal power of 10 MW consumes 48 tonnes of fuel per day (on the assumption that the specific fuel consumption is 200 g/kWh). Due to the significant air pollution and high costs of operating marine engines as a result of fuel consumption, engineers and scientists must improve the in-cylinder processes so that the combustion is cleaner and more efficient.

The combustion process in a diesel engine cylinder is mainly determined by the fuel injection process (Zhou *et al.*, 2019). Fuel delivered by the injector is atomized and simultaneously evaporated and mixed with air/exhaust gas mixture and burnt. According to Payri et al. (Payri *et al.*, 2015), five phases may be observed in fuel tip propagation: (I) non-reaction, (II) auto-ignition expansion, (III) stabilization, (IV) acceleration, and (V) quasi-steady propagation. The first phase is usually divided into two stages: primary and secondary break-up (Hiroyasu and Arai, 1990). Fuel is delivered and atomized to the cylinder under high pressure. The atomized fuel creates a cloud of droplets in a conical shape. The conical cloud of droplets is described by two main parameters: spray tip penetration (STP) and spray cone angle (SCA) (Figure 3.) and micro-parameters such as Sauter Mean Diameter (SMD) or the average droplet diameter. It has been

shown that these phenomena are determined by the dimensions of the fuel nozzle holes, the fuel flow, the pressure in the engine cylinder, and the properties of the fuel.

In the literature, there are many studies numerical and experimental concerning the parameters of fuel injection depending on the injection pressure (Chen *et al.*, 2019; Lei *et al.*, 2019; Vaid *et al.*, 2014), backpressure (ambient pressure in the engine cylinder)(Jing *et al.*, 2017; Payri *et al.*, 2009, 2017), and shape of the nozzle holes (Wang *et al.*, 2015) including their conicity, which is defined by the K factor (Feng *et al.*, 2016; Som *et al.*, 2011), K = 1 for cylindrical holes. According to results obtained by Payri et al. (Payri *et al.*, 2008), an increase of the K factor causes an increase of the SCA. The method of fuel injector activation affects the parameters of the fuel spray as well. In (Yu *et al.*, 2017) and (Suh *et al.*, 2007), measurement results for piezo- and solenoid-driven fuel injectors were presented. The energizing of the fuel injector by a piezoelectric system with a fuel injection pressure of 60 MPa causes lower tip penetration and a higher SCA compared to energizing by a solenoid system. An analysis of adjacent fuel injection holes (Nishida *et al.*, 2009) is also available. Most researchers assume that the break-up process is determined by cavitation phenomena on the rough surfaces of the nozzle holes (Liu *et al.*, 2018; Wang, 2013). Most researches are limited to the injection process of the general Diesel engine. Therefore, the injection system and fuel spray parameters of marine diesel engine with the large nozzle length/diameter (L/D) with operating parameters the same as in a marine diesel engine is studied rarely. The cavitation phenomena is important design criterion of the fuel injection system and spray characteristics in marine Diesel engines.

Yan et all. (Yan *et al.*, 2016) studied effect of injection pressure on cavitation and spray in marine diesel engine. In this studied was used to simulate cavitation and spray two – phase flow model combined with single bubble dynamics and a droplet break-up model. The numerical simulation results was compared to the experimental data. In the research of marine injectors, an increasing development of numerical simulation test is observed. Balz R.(Balz *et al.*, 2021) and all presents numerical and experimental investigation of cavitation in marine Diesel injectors. They showed that, experimental in-nozzle flow visualization has shown cavitation patterns in the nozzle bore. It is determined that, the geometric characteristics of nozzle bore location and its direction have a dominant effect on the type and evaluation of cavitation formation. The additional have been executed CFD simulation results in order to validation results. With the development of research on alternative fuels, there are a lot of studies on the characteristics of the fuel spray and combustion of fuels other than diesel (Adamczyk *et al.*, 2020; Cai and Abraham, 2017; Yu, 2019).

It should be emphasized that the available publications concerning fuel injectors and injection conditions usually treat those occurring in diesel engines with small dimensions compared to marine engines (Kostas *et al.*, 2009). According to Kowalski (Kowalski, 2014), the diameter of the nozzle holes in marine fuel injectors is commonly larger than 0.3 mm. The fuel injection pressure is similar at 40 MPa (except for common rail systems) and the backpressure exceeds 4 MPa at the instant of injection. The largest observed diameter of a nozzle hole (0.3 mm) is presented in (Lee and Park, 2002), but under higher fuel injection pressure. The parameters of the fuel spray are determined using mathematical models

presented in the literature. The many developed models of diesel STP are elaborated based on the assumptions made by Hiroyasu and Arai (Hiroyasu and Arai, 1990) or Naber and Siebers (Naber and Siebers, 1996). The fuel atomization model of Hiroyasu and Arai is used for the analysis of experimental research and the rating of the validity their results. This model assumes that STP is linearly proportional to the time only in the early injection period. The values of the various spray parameters depend on time, ambient gas density, backpressures and differences in fuel specifications. After the period of time in which the STP has a linear proportionality, it has been found to be proportional to the square root of the elapsed time. In the period of time in which it is proportional to the square root of the elapsed time, geometrical parameters of the fuel nozzle, such as the diameter, must be taken into account. The other models of fuel STP described in the literature are similar to that of Hiroyasu and Arai and are in general two-step (Bohl *et al.*, 2017; Kostas *et al.*, 2009) including t_B. According to these models, the initial step before t_B does not include the geometrical parameters of the fuel nozzle. But usually SCA and STP are measured for fully developed spray (Bohl *et al.*, 2017; Hiroyasu and Arai, 1990; Reitz and Bracco, 1979). In a marine diesel engine, the start of combustion is much earlier (Kowalski, 2016). Hence, the present authors believe that the description of the early stage of fuel spray is most important to understand and describe the combustion process in the engine cylinder. The second novelty area, in comparison to other works, is the finding of a dependence between the geometrical parameters of the fuel nozzle and the fuel spray geometry at the early stage of injection. This problem is omitted in the model of Hiroyasu and Arai and other models.

The main target of the present paper is to propose a new model of STP and SCA for large injectors. On the basis of experimental research, new models are proposed for the early stage of fuel spray, taking into account the geometry of a large fuel injector. The model is obtained on the basis of experimental results and a modification of the Hiroyasu and Arai model.

2 Laboratory setup

The research was conducted in a constant-volume chamber with a quartz window providing 100-mm optical access (Figure 1.) (Grochowalska, 2019). The injector used is a conventional pressure-opened diesel injector from a Sulzer Al 25/30 type marine engine equipped with a Unit Pump injection system. The injector was located at the top of the chamber. This setup allows observing the evolution of a single fuel jet at a distance of almost 100 mm (half of the cylinder bore). The fuel was supplied to the injector by a high-pressure common rail system equipped with a fast-acting electromagnetic valve releasing fuel flow to the injector. The pressure behind the injector was measured by means of a Kistler type 4067E (Kistler, 2014) piezorezistive pressure sensor.

The spray inside the chamber was observed by means of the Mie scattering technique (Grochowalska, 2019; Piazzullo *et al.*, 2017). The spray was illuminated in a visible range of wavelengths as in Zigan et al (Zigan *et al.*, 2011). Mie scattering results may differ greatly depending on the type of spray illumination.

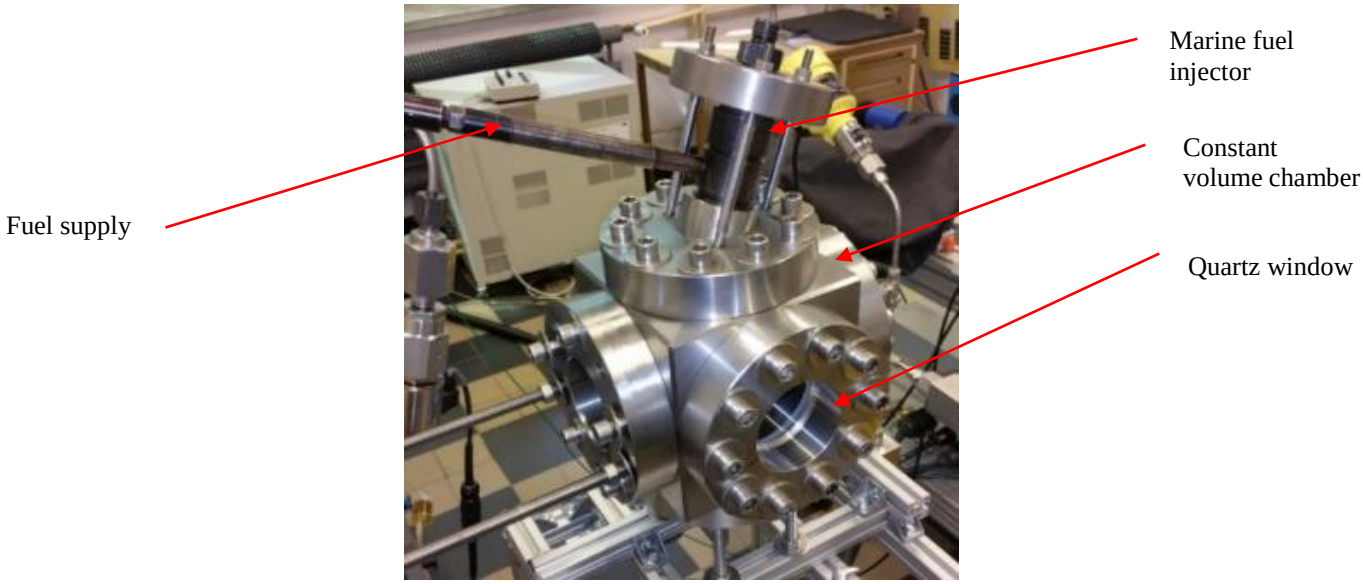

Figure 1. Constant-volume chamber with injector on the top (Grochowalska, 2019)

Light sheet illumination is necessary when visualizing hollow cone sprays. As far as cylindrical nozzle sprays are concerned, the integral type of illumination performs very well, especially in the determination of global spray parameters. In this study, both SCA and STP were determined and therefore the integral illumination of the spray was chosen. For this purpose, two externally located halogen lights (0.5 kW each) were used. The illuminated sprays were observed by a Photron SA1.1 high-speed camera. The resolution of the recorded images was 512 × 256 pixels. The images were recorded at a frequency of 40 kHz. A schematic of the experimental setup is shown in Figure 2.

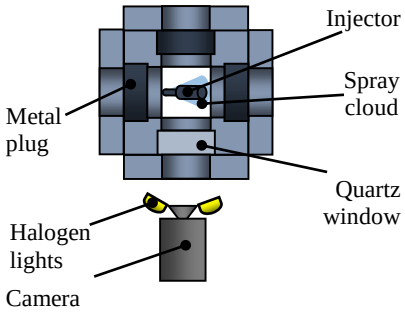

Figure 2. The experimental setup

Table I. Nozzle parameters

	Diameter (D) [µm]	**Ratio $\frac{L}{D}$**	**K factor** (Som *et al.*, 2011)
Nozzle 1	285	10.9	1
Nozzle 2	325	9.5	1
Nozzle 3	375	8.3	1

The injection process was tested for three different nozzle diameters. The ratio $\frac{L}{D}$ (L is the length of the nozzle and D is its diameter) is presented in Table I. The fuel pressure in the common rail system was 50 MPa. The injector opening pressure was adjusted to 25 MPa (the same as in the Al 25/30 marine engine). Each nozzle was tested at two different backpressures: 3.2 and 4.3 MPa, corresponding to half- and full-load engine operation, respectively. The measurement was repeated three times at each point. The temperature during the test was 300 K. The measured diesel oil viscosity and density were equal to 2.35 mPa*s and 816.1 kg/m^3, respectively, at 40 °C. The obtained images were processed by DaVis v8.4 software.

3 Results and discussion

Figure 3 presents an example of the resulting macro-parameters of the tested diesel spray. STP is defined as the distance from the nozzle to the front of the spray (Feng *et al.*, 2016; Heywood, 1988). According to the presented results, the spray direction is determined by three lines: two on the boundaries on the left and right sides and the third being the line of the nozzle symmetry. Interpolation of the left and right sides of the boundary was performed.

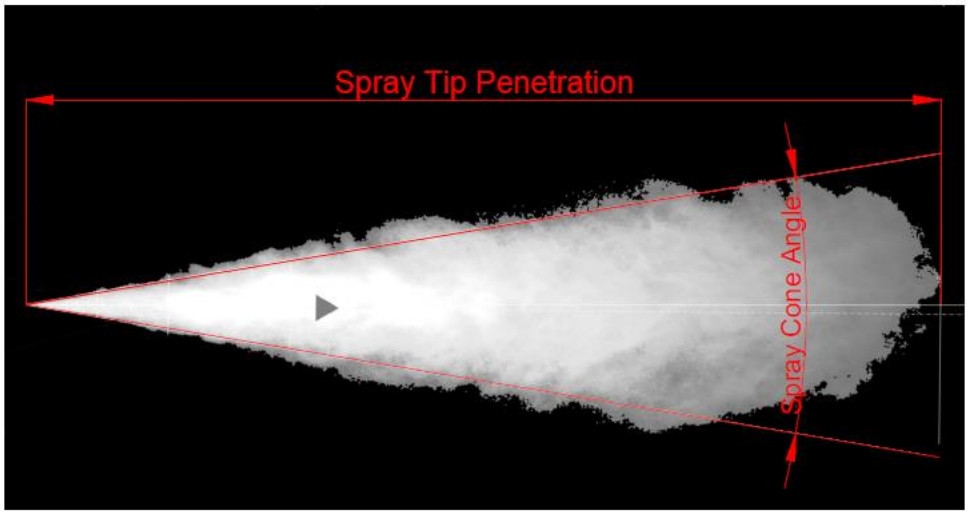

Figure 3. Schematic of diesel fuel spray defining its macro-parameters

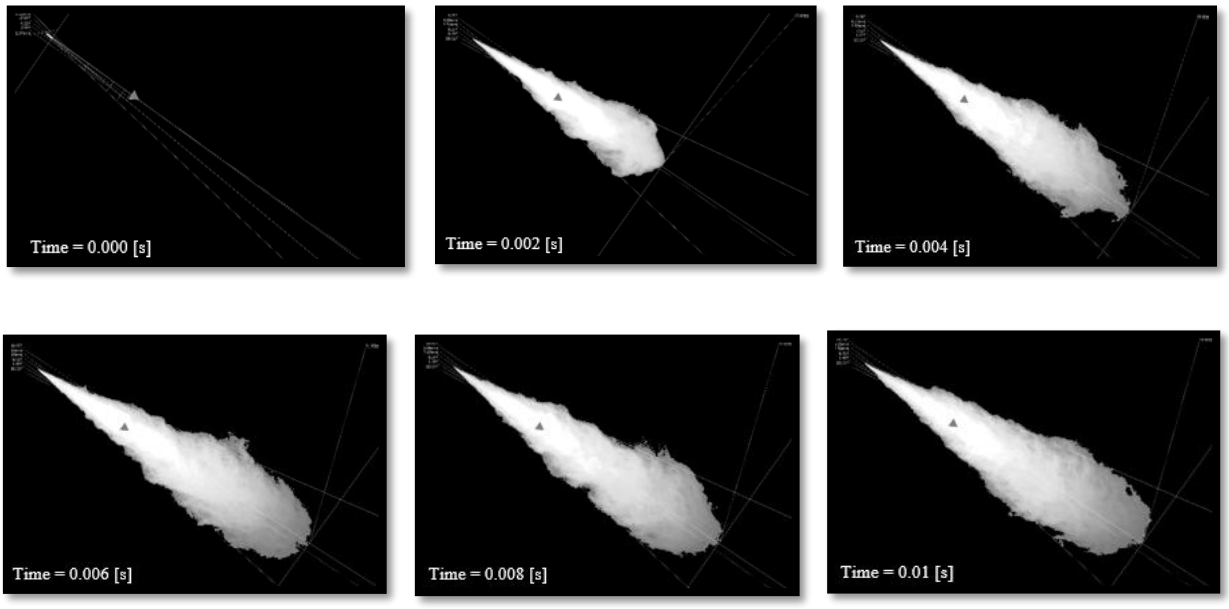

Figure 4. Mie scattering spray image for nozzle 2 with a backpressure of 4.3 MPa

The analysis of the macrostructure of the fuel spray was conducted using 250 frames for each injection process, which covered the range from the beginning of the injection to the complete development of the spray. Figure 4 shows selected images presenting the development of the diesel fuel spray for nozzle 2 with a backpressure of 4.3 MPa. The measurements and received series of images depicting the diesel spray from the injector were recorded. Prior to the calculation of the macro-parameters of the diesel spray, pictures had to be prepared. The first stage of image processing was scaling from pixels to millimeters with verification of the nozzle position in the picture. One pixel is equal to 0.13 mm in this study. Secondly, the spray isolator function was used to separate the spray from the ambient and to eliminate reflections and image noises within a short distance from the spray. The prepared series of images was used to define the STP and SCA, and propose a new model for these parameters.

3.1 Spray Tip Penetration

Figure 5 presents the results of the STP measurements. The presented test results are the arithmetic mean of three observations of the measurement and are qualitatively similar to the results presented in (Cai and Abraham, 2017; Siebers, 1999). Comparing these with the results of combustion in the AL25/30 engine from (Kowalski, 2014) it should be noted that the start of combustion is when the cloud of the fuel spray is not fully developed. These charts contain data only up to 0.0004 s (the cloud of the fuel spray is not fully developed). According to Siebers (Siebers, 1999), the maximum STP of fuel spray increases linearly with the increasing of nozzle diameter. This trend was observed in experimental results in the early stage of STP.

In the standard combustion chamber conditions the maximum liquid spray distance is limited by hot air entrainment rate and mixing of fuel and air (Siebers, 1999). First of all, the energy needed for evaporation of the fuel results from the high ambient temperature in the cylinder of a diesel engine. The above evaporation is influenced by nozzle diameters, hot air

entrainment rate and properties of the fuel. A decrease of the nozzle diameter causes a reduction of the size of the fuel droplets produced and lowers their speed. This finding was presented in the test results in (Som *et al.*, 2011). It is important to mention that decreasing $\frac{L}{D}$ (the increase of the nozzle diameter in this case) may cause a turbulent flow inside the nozzle and cavitation (Yao *et al.*, 2016) which could also influence the results obtained here. Naturally, when the distance from the nozzle increases, the diameters of the droplets in the fuel spray decrease (Yu, 2019). As ambient gas density increases, spray dispersion increases, which results in more entrained air particle in the spray. The larger entrained mass leads to a slower penetration velocity based on conservation of momentum, and therefore, reduced penetration (Balz *et al.*, 2020). This is caused by the aerodynamic resistance in the constant volume chamber (secondary break-up). The influence of increasing backpressure on reducing the STP was shown in (Grochowalska, 2019; Payri *et al.*, 2017; Wang *et al.*, 2016) and (Yan *et al.*, 2016)and are confirmed by the present results. On the basis of the analysis in Figure 5 and (Grochowalska, 2019), it may be concluded that an increase of backpressure generally causes a reduction of STP for big nozzles. The reason for this is the formation of large droplets at the exit of the fuel injector nozzle about the big diameter of the outlet nozzle. The large droplets break up longer in time under the influence of backpressure, but also have a higher growth rate at the very beginning compared to the diameter droplets formation by the smaller diameter of the outlet nozzle. The higher growth rate of STP was shown in Figure 6. The growth rate of STP was particularly higher for a big nozzle at a backpressure of 3.2 MPa than at 4.3 MPa. It should be noted that the working space of the constant volume chamber was filled with nitrogen. As is well known, nitrogen has a lower density than oxygen contained in the air. Therefore, the experimental results of STP are valid only for the considered condition.

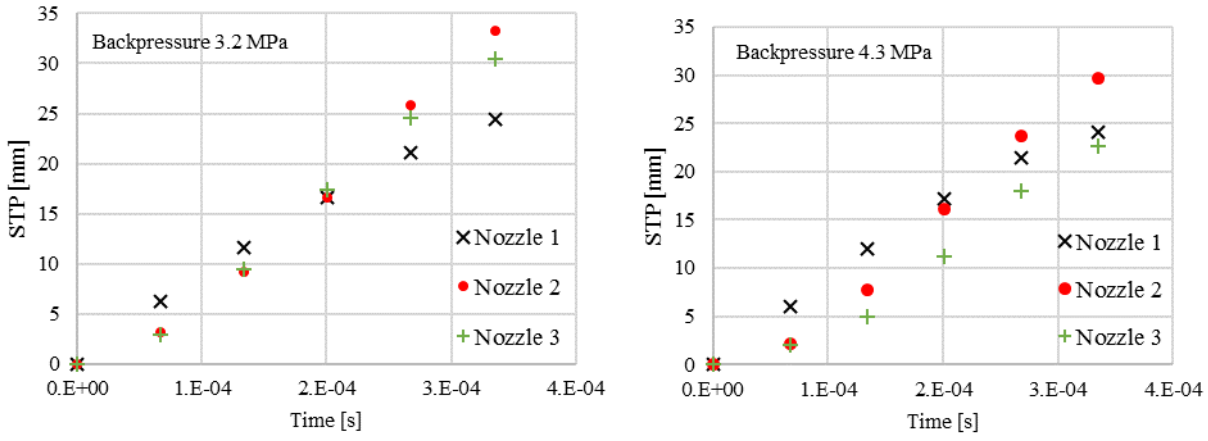

Figure 5. STP for the nozzles 1, 2, and 3 with backpressures of 3.2 MPa and 4.3 MPa

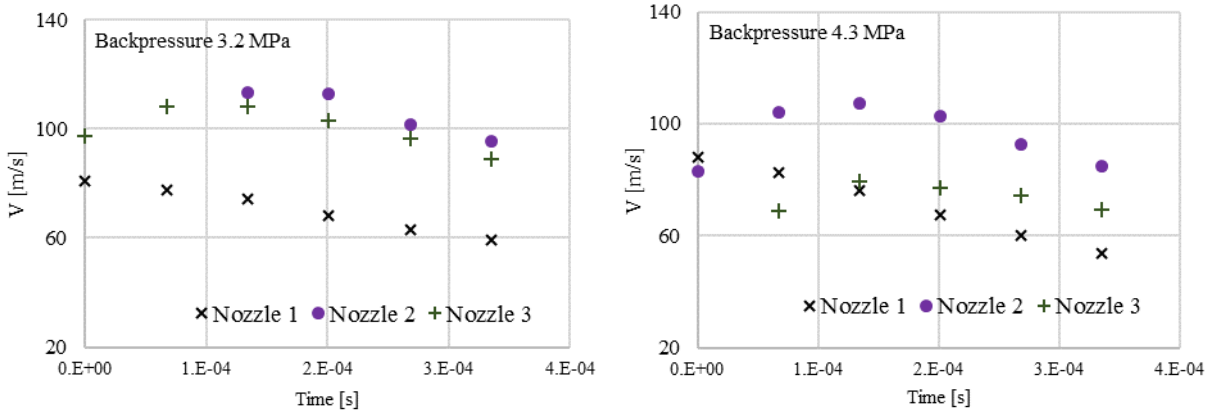

Figure 6. Growth rate of STP for backpressures of 3.2 MPa and 4.3 MPa

3.1.1 Model for spray tip penetration

The temporal development of the STP in the combustion chamber of diesel engines has been examined and described for many years. Generally, many correlations come from the work of Hiroyasu and Arai (Hiroyasu and Arai, 1990). These correlations were used for comparison purposes in this paper. The Hiroyasu and Arai model was verified at low injection pressure and backpressure. Therefore, the theoretical correlations were believed appropriate in analysis of the dependencies of the spray parameters of a marine diesel engine. Hiroyasu proposed that during the early stage of fuel injection the spray penetration is proportional to time [linear stage (1)], while at later stages it is proportional to the square root of the time (2). The time when the transition occurs is referred to as the breakup time t_b (3). The Hiroyasu and Arai model is presented in the form:

$$STP(t) = 0.39\sqrt{\left(\frac{2\,\Delta P}{\rho_f}\right)}t \ldots .0 < t < t_b \quad (1)$$

$$STP(t) = 2.95\left(\frac{\Delta P}{\rho_f}\right)^{\frac{1}{4}}\sqrt{(Dt)} \ldots t > t_b \quad (2)$$

$$t_b = 29\frac{\rho_f D}{(\rho_a \Delta P)^{0.5}} \quad (3)$$

STP (t)- STP (m), ΔP – difference between fuel pressure in the nozzle and the ambient pressure (Pa), ρ_f-fuel density (kg/m^3), D-nozzle diameter (m), t-time (s).

According to the results presented in Figure 5, a linear model of STP may be adopted from the start of injection (SOI) to (2.0-3.4) x10-4 s, depending on the backpressure and nozzle diameter (time t_b). A smaller nozzle diameter and higher backpressure cause a decrease in t_b. According to the Hiroyasu and Arai model, the STP at the beginning of the injection does not depend on the nozzle diameter, but the measurement results show that this is not true. The initial stage of the experimental evolution of STP for all cases is very similar but not the same. Figure 5 shows the STP of the initial stage in the charts up to 0.0004 s, in which it can be seen that there are differences, as depicted. Geometrical parameters such as the length to diameter ratio of the fuel nozzle have a significant effect on the STP in the considered nozzles. The

influence of this ratio on liquid length spray penetration was found by Siebers (Siebers, 1999) who found a linear relation between the nozzle hole diameters and liquid spray penetration, but only for fully developed fuel spray. The early stage STP model of Hiroyasu and Arai does not include changes in the nozzle diameter, but only the difference between the fuel injection pressure and backpressure. As one of the main parameters of influence on the STP of fuel spray there is the difference between the pressure into the nozzle and the backpressure in the constant volume chamber, which was included in the Hiroyasu and Arai model. Therefore, in the presented experimental tests, the fuel pressure in the fuel line was measured. The diesel fuel pressure was maintained by a fuel pump. The fuel pressure sensor was located in the fuel line in front of the fuel injector (Section 2 *Laboratory setup*). The fuel pressure before the exit nozzle is equal to the fuel line pressure. Opening the fuel injector caused fuel to flow and temporarily change the pressure in the fuel line to be the same as in the nozzle. At first there follows a sharp rises of the fuel pressure, which then becomes stable. The temporary fuel pressure change in the fuel line and fuel spray propagation in the constant volume chamber continued simultaneously. In (Lei *et al.*, 2019) there was presented research about the effect of the injection behavior on fuel spray penetration, confirming the influence of the fuel pressure on the characteristics of the spray. Therefore pressure changes should be taken into consideration. Figure 7 presents the early stage of the experimental data of STP to time 0.0004 ms of the development of the fuel spray and the Hiroyasu and Arai model based on the experimental input data.

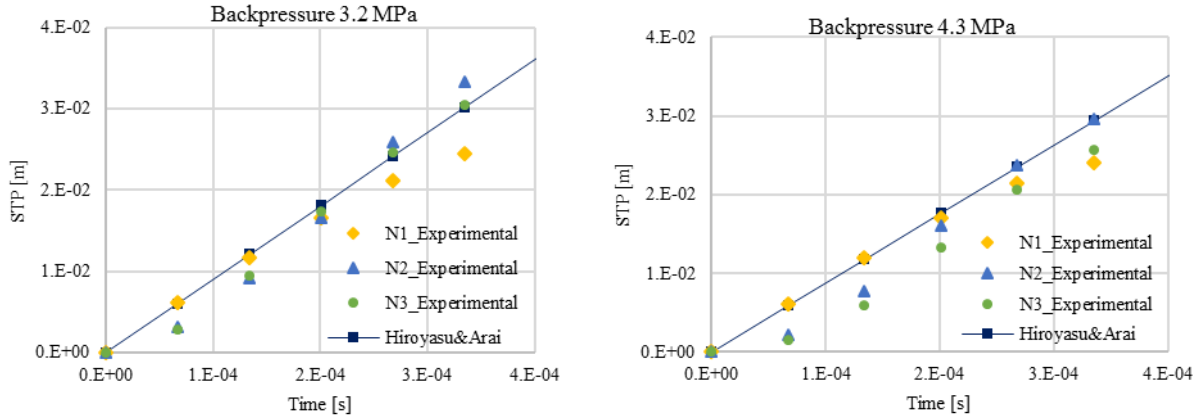

Figure 7. Early stage of the experimental data of STP and Hiroyasu and Arai model on based experimental input data

In Figure 7 there can be observed differences between the experimental results and the Hiroyasu and Arai model for the considered backpressures. The average relative error between the experimental results and the Hiroyasu and Arai model is in the range 19%-38% (Figure 9). Therefore, it can be suggested that a mathematical model of linear STP should be extended to include the influence of the nozzle diameters. The present analysis shows that Equation 1 of the Hiroyasu and Arai model should be extended for the considered experimental results to the following form:

$$STP(t) = 0.0641 \cdot \left(\frac{L}{D} + 1\right) \sqrt{\left(\frac{2\Delta P}{\rho_f}\right)} \cdot t \qquad (4)$$

- ratio $\frac{L}{D}$, L- nozzle length [m], D – nozzle diameter [m];

Examples of the results of the new model of the STP for Nozzle 1 are presented in Figure 8.

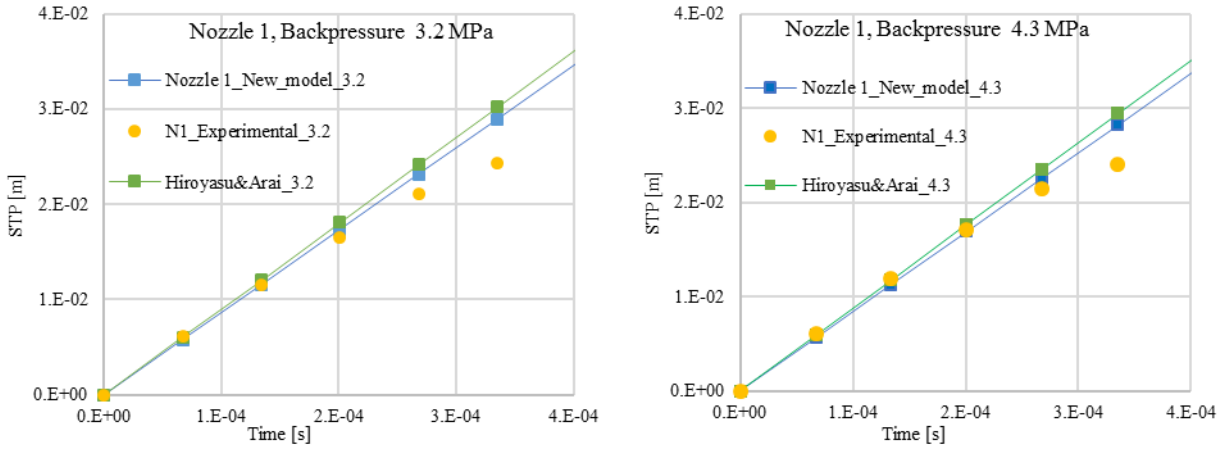

Figure 8. Early stage of the STP for new model, experimental data and Hiroyasu and Arai model

The results of the modified model for STP agree with the experimental data. By introducing the ratio $\frac{L}{D}$ it is possible to adjust the model results to the experimental data for different nozzle geometries in the early stage of injection.

Figure 9 presents the calculated relative errors of the Hiroyasu and Arai model and the proposed STP model for the early stage of injection in comparison to the experimental results. A general analysis shows that the proposed model gives a lower average error in relation to the experimental results compared with the Hiroyasu and Arai model. The decrease of the mentioned error is about 15%-34% for the considered parameters in dependence on the fuel nozzle geometry.

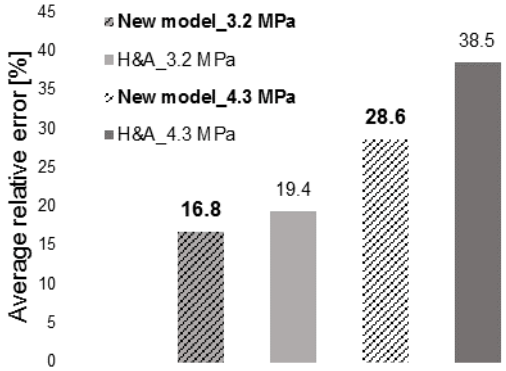

Figure 9. Average relative error between experimental of STP and new model of STP for all considered nozzles

3.2 Spray cone angle

Figure 10 presents the evolution of the SCA with time for the considered nozzles and backpressures. In the early stage (from the SOI up to 0.001 s), the increase of the SCA can be observed for all of the tested nozzles. The value of the maximum SCA for diesel oil and different diameters of nozzles changes in a range of about 16°–20°. Nevertheless,

depending on the geometrical parameters of the injector nozzle, the growth rate of the SCA differs. When the nozzle diameter is increased and $\frac{L}{D}$ is decreased, it is possible to observe a decrease of the SCA at all considered backpressures, as shown in Figure 10. This is probably caused by the need for a longer time for the break-up and partial evaporation of the droplets produced by nozzles with bigger diameters.

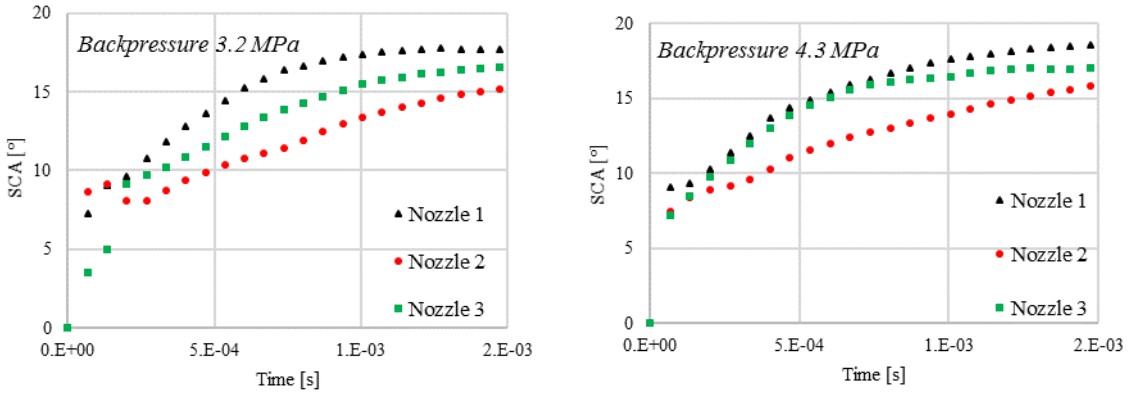

Figure 10. SCA for considered nozzles 1, 2, 3 and backpressures

The influence of the backpressure on the SCA was also observed. This is confirmed by (Feng *et al.*, 2016) and Figure 10. This is particularly observed for big nozzles of a fuel injector. An increased density of the surrounding gas causes a higher growth in the radial direction than in the axial one. As mentioned before, the difference between the fuel pressure and the backpressure influences the fuel spray. Therefore, Figure 11 shows the course over time of SCA in dependence on the difference between the injection pressure of the fuel injector and the backpressure into the constant volume chamber (ΔP). It should be noted that the injection pressure was changed in time, but the backpressure was almost constant.

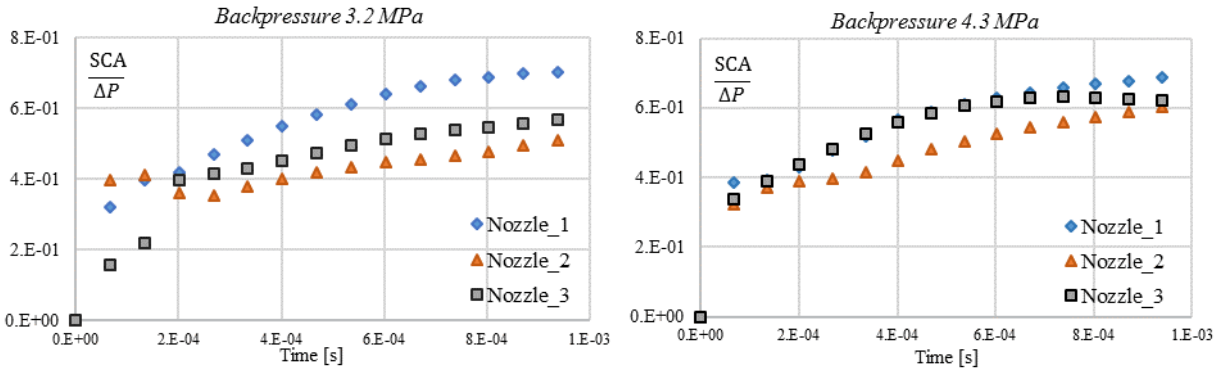

Figure 11. (SCA/ΔP) ratio over time for considered nozzles and backpressures

Additionally, the value of the SCA may be influenced by cavitation occurring at the end of the nozzle (Balz *et al.*, 2020). The formation of cavitation bubbles at the exit of the nozzle may cause greater dissipation and an increase of the value of the SCA (Sou *et al.*, 2007). For nozzles 2 and 3 there was observed a significant effect of a change in the difference

between the pressures on the SCA in time (Grochowalska, 2019). This is related to the formation of large droplets in the fuel spray at the beginning and the aerodynamic resistance in the constant volume chamber. An increase of backpressure in the constant volume chamber caused a decrease in the influence of the difference between the pressures on SCA for nozzle 2 and nozzle 3.

Generalizing this observation, a change in the fuel pressure in the fuel line over time in relation to the backpressure on the exit injection nozzle has an influence on the SCA. This influence on the SCA decreases over time. The second observation is that an increase of the backpressure on the exit of the fuel nozzle causes a decrease in the influence of the pressure change on the value of the SCA over time.

3.2.1 Model for the Spray Cone Angle

The existing mathematical models for SCA represent constant angles through the whole time of the development of the spray (Heywood, 1988; Kegl and Lešnik, 2018; Reitz and Bracco, 1979). The models in the literature include some characteristics of the nozzle and parameters of the injection process, fuel properties and spray environmental conditions. In the present paper, the Hiroyasu and Arai model of the SCA was selected for comparison with the experimental data. That model was presented in Equation (5), and Table II presents the SCA for the experimental and calculated results.

$$SCA = 83.5\left(\frac{L}{D}\right)^{-0.22} \cdot \left(\frac{D_0}{D_{sac}}\right)^{0.15} \cdot \left(\frac{\rho_g}{\rho_f}\right)^{0.26}, \quad (5)$$

Where: D_{sac} – the diameter of injector sac;

Table.II SCA [°] by Hiroyasu and Arai Model and experimental data

Nozzle	Backpressure 3.2 MPa (H&A model)	Experimental Average 3.2 MPa	Backpressure 4.3 MPa (H&A model)	Experimental Average 4.3 MPa
1	12.97	17	14.00	19
2	13.63	16	14.71	18
3	14.34	17	15.49	17

The experimental SCA for the considered large nozzles were higher in comparison to results from the Hiroyasu and Arai model**.** Auto ignition of the air-fuel mixture in the cylinder of the marine engine occurs when the fuel spray does not reach its maximum development parameters. Therefore, it is important to develop a model of the change in the SCA over time. The first five measurements of SCA were omitted from the analysis due to their great dispersion, probably caused by measurement inaccuracy. The mentioned measurements results have a large error due to the difficulties in processing the photographic results. The SCA at the beginning of the course at the time was difficult to estimate. The proposed model presented in this paper Equation (6) was developed on the basis of dependencies defined by combining terms from existing

models. When analyzing the experimental results, one can notice the logarithmic function of the early stage of the evolution of the SCA over time.

Using this as the basis, the following proposed model of SCA was formulated:

$$SCA = \left[-0.462 \cdot \frac{L}{D} + \sqrt{\Delta P} \cdot \left(\frac{\rho_f}{\rho_g}\right)^{0.2}\right] ln(t) + (3.17 \cdot \Delta P - 28.067), \quad (6)$$

By analyzing all considered cases, the average of relative error of proposed model of SCA over time is 20% for backpressure 3.2 MPa and 17% for backpressure 4.3 MPa.

4 Conclusions

The macrostructure of diesel oil spray from a marine engine injector was characterized using the Mie scattering method. The parameters that were measured were the spray tip penetration (STP) and the spray cone angle (SCA). These parameters were analyzed in terms of three different nozzle diameters and two backpressures 3.2 and 4.3 MPa corresponding to engine operation under half and full loads, respectively. The main theories concerning the influence of the geometric parameters of the injector nozzle on STP and SCA were confirmed:

- Increasing the diameter D of the injector nozzle or decreasing the ratio $\frac{L}{D}$ (where L is the length of the nozzle) increases the STP and SCA;
- Changing the backpressure from 3.2 to 4.3 MPa decreases the STP and increases the SCA.

The early stage of STP was described based on the Hiroyasu and Arai model. But the proposed model also includes a dependence on $\frac{L}{D}$. Additionally, a model for SCA was developed which assumes a logarithmic dependence of the SCA on time. The average of the relative error of the proposed model from the experimental results was about 18%. The new mathematical models of the fuel spray parameters used in this work were obtained on the basis of experimental work with specific conditions. Therefore, the mathematical models of SCA and early STP are specified for specific conditions such as the geometrical parameters of a marine injector, the injection pressure, and the backpressure into a constant volume chamber.

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